APPENDIX P -- THE EFFECTS OF FRESHWATER INFLOW, INLET CONVEYANCE AND SEA LEVEL RISE ON THE SALINITY REGIME IN THE LOXAHATCHEE ESTUARY

Guangdou "Gordon" Hu, Ph.D., PE *Coastal Ecosystems Department*

CONTENTS

Abstract

The upstream migration of salt water into the historic freshwater reaches of the Loxahatchee River is the likely cause of the altered floodplain cypress forest community along the Northwest Fork and some of its tributaries. Mangroves are replacing cypress forest and areas of mixed swamp hardwoods have reacted to different degrees to the saltwater stress. A hydrodynamic/salinity model was developed to study the influence of freshwater input, tidal inlet deepening and sea level rise on the salinity regime in the estuary.

Field data analysis and model simulations indicate that the salinity condition in the estuary is sensitive to the amount of freshwater input from the watershed. During dry seasons the salt front advances into areas that were historically freshwater habitats.

Historic evidence indicates that the Loxahatchee estuary was periodically closed and opened to the sea. Due to the active long shore sediment transport, the tidal inlet was probably characterized by shifting sandbars through which ran a narrow and unstable channel. Inlet dredging in the past several decades has increased the hydraulic conveyance of the inlet and the tidal influence into the estuary.

The sea level record from a site in south Florida indicates that the sea level has been rising at a rate of approximately 2.3-mm per year. The rise of sea level in the past century has probably raised the mean tide level by about 23 centimeters. If the sea level rise continues as predicted, it is foreseeable that the salt front will move further upstream along with the sea level rise.

Field data analysis and the preliminary model output led us to believe that the advance of seawater up the estuary is the combined effect of watershed hydrological changes, inlet deepening and sea level rise.

Keywords: estuary; freshwater inflow; sea level rise; salinity; saltwater intrusion

INTRODUCTION

The Loxahatchee River estuary empties into the Atlantic Ocean at Jupiter Inlet in southeastern Florida. The estuarine system is comprised of three forks: the Southwest Fork, North Fork, and Northwest Fork (Figure 1). Estuarine conditions extend from Jupiter Inlet to about 5 river miles up the Southwest Fork, 6 river miles up the North Fork, and 10 river miles up the Northwest Fork. Four tributaries; Loxahatchee River, Cypress Creek, Hobe Grove Ditch, and Kitching Creek discharge to the Northwest Fork. Canal 18 (C-18), built in 1957 – 1958, is the major tributary to the Southwest Fork. The North Fork has several small unnamed tributaries. Rainfall in the area is seasonal, 5 inches per month is common during the wet season from

May through October. Amounts near 2.5 inches per month generally occur during the dry season from November to April (Russell and Goodwin, 1987).

The upstream migration of salt water into the historic freshwater reaches of the Loxahatchee River is the likely cause of the altered floodplain cypress forest community along the Northwest Fork and some of its tributaries. A hydrodynamic/salinity model was developed to study the influence of freshwater input on the salinity conditions in the river and estuary. The hydrodynamic model was calibrated against National Ocean Service (NOS) data for a three-month period from December 1996 to February 1997. The tidal output was then verified against NOS data for a four-month period from January 1999 to April 1999. The salinity model was calibrated and verified against field data that were collected from January to June of 1999. The model was applied to scenarios with varying amounts of freshwater inflow. Both the field data and model simulation indicated that there is a strong correlation between freshwater inflow and the salinity regime in the estuary. Based on model output and field data analysis, a relationship was developed to predict salinity at various points in the estuary with respect to freshwater inflow rates and tidal fluctuations. The model was also used to provide a preliminary assessment of the impacts that inlet deepening and sea level rise have had on the salinity regime in the estuary.

METHODS

The software used in the development of the Loxahatchee River Hydrodynamics/Salinity Model were computer programs RMA-2 and RMA-4, which were developed by Resource Management Associates (RMA) and the Army Corps of Engineers (USACE, 1996). The model mesh was formed from a total of 4736 topographic data points derived from survey data. The XY coordinates and elevation of the 4736 points provide the geometry of the model. Figure 1 shows the finite element model mesh that was developed for this modeling study. The available bathymetric data does not cover the upstream portion of the Northwest Fork. The model mesh in Figure 1 used average depths, which were reported by a previous study, for that portion of the river (Russell and Goodwin, 1987). The model mesh will be updated when the bathymetric data for the upper Northwest Fork are collected.

Freshwater inflow data were available from three flow gages. The gage on the upper Northwest Fork at Lainhart Dam controls about forty to fifty percent of total freshwater input to the Northwest Fork. The other two gages are located on the North Fork, and on the Southwest Fork at flow control structure S-46 (Figure 1). The freshwater input from Cypress Creek, Hobe Grove and Kitching Creek was estimated based on a previous study by USGS (Russell and McPherson, 1983). Based on flow data from these tributaries and Lainhart Dam, the report established ratios between discharge from each tributary and the discharge at Lainhart Dam. These ratios were used to estimate the discharge from these tributaries.

The hydrodynamic model was calibrated against NOS data for a three-month period from December 1996 to February 1997. The tidal output was verified against NOS data for a four-month period from January 1999 to April 1999. Figure 2 is the comparison of model output and NOS predicted tide at the station Boy Scout Dock on the Northwest Fork (Figure 1). This station is the most upstream (inland) station that is listed in the NOS Tide Table. Model output was also verified against data from other NOS sites at the Middle and Lower Estuary and at the Jupiter Inlet.

Calibration of the salinity model was based on flow and salinity records from January 1 to April 30, 1999. The period includes a typical transition from wet season to dry season. While the flow record at Lainhart Dam shows a decreasing freshwater inflow to the estuary, the salinity records indicate that the salinity increased significantly, even at the upstream portion of the estuary. Figure 3 and 4 are comparisons between model output and the field records at Station 64 (River Mile 7.7) and Station 65 (River Mile 8.6).

Model verification was based on the field records of the subsequent two months - May and June 1999. Starting in May, the freshwater inflow increased and salinity level dropped accordingly. Model output was depicted with two different colors in Figure 4. The first portion shows the results of the model calibration. The second portion shows results of the model verification. Figure 5 is the verification results at Station 66 (River Mile 9.4).

While the model output followed the overall trend of salinity changes, it did not track all the short term variations that were observed in the field. Field data indicates that salinity in the upper estuary is extremely sensitive to the amount of freshwater input. Since approximately fifty to sixty percent of the freshwater input was estimated based on a set of fixed ratios, the amount of total freshwater input apparently did not accurately reflect the short term variations of flow discharge from tributaries. Such inaccuracy would in turn cause error in salinity prediction. On the other hand, over longer periods these ratios seem to have produced a relatively accurate estimate of the overall amount of freshwater input to the estuary. As a result, the model was able to follow the overall trend of salinity changes indicated by the field data. New flow stations are currently being deployed on major tributaries. The model will be re-calibrated when a more complete data set becomes available.

The model applications included eleven simulations at various levels of freshwater input to develop flow versus salinity relationship. The estuarine salinity regime is the result of a dynamic process that involves mainly tides and freshwater inflow. Salinity fluctuates constantly in response to changes in tides and freshwater inflow. Even if the freshwater inflow is constant, there is a significant variation in salinity within each tidal cycle. The variation in range between spring and neap tides is another major factor that affects the salinity. A 28-day tidal cycle with two spring tides and two neap tides was chosen for all the flow scenario simulations. The model predicts salinity for each of the over 3000 nodes at 30-minute intervals. The model output was filtered to select high tide and low tide salinity. The 56 high tide salinity values and 56 low tide salinity values were averaged to find the mean high tide salinity and the mean low tide salinity for the 28-day period.

RESULTS

The Influence of Freshwater Input on the Salinity Regime in the Estuary

The results of eleven model simulations at various levels of freshwater input are condensed into two color plates (Figure 6 and 7). The curves in Figure 6 and 7 represent the flow versus salinity relationship at 7 sites in the Northwest Fork. On the horizontal axis of these charts, the amount of freshwater input was represented by the flow rate at the Lainhart Dam. The corresponding salinity for the given flow can be read from the vertical axis. Salinity given by Figure 6 is mean high tide salinity. Figure 7 gives mean low tide salinity. Combined, these two charts can be used to predict high tide and low tide salinity values in the Northwest Fork for a given freshwater discharge.

The model output is consistent with the results of field measurements and indicates a correlation between salinity in the estuary and freshwater inflow rate. The correlation appears to be the strongest in the upper Northwest Fork. When freshwater discharge at the Lainhart Dam decreases to approximately 35 cubic feet per second (cfs), salinity in a large portion of the Northwest Fork will exceed two parts per thousand (ppt). Both the field data and model results indicate that a change of freshwater input as small as 10 cfs can cause detectable salinity changes in this area.

To facilitate management decisions, maps of 2-ppt salinity lines were prepared based on model output (Figure 8 and 9). Figure 8 shows the spatial positions of 2-ppt salinity lines with various freshwater inflow rates at high tide. Figure 9 shows the locations of 2-ppt lines at low tide.

The difference between spring and neap tides is also a significant factor. To present the 2-ppt lines under an average tide condition, the results in Figure 8 and 9 were created based on a tide range of 2.48 ft at Jupiter Inlet. The mean tidal range at the inlet is 2.46 ft, according to NOS data. Therefore the results presented on the maps represent an "average tidal condition." The 2-ppt lines shown in these maps will be at about the middle point between the position of the salt front at spring tides and at the neap tides.

The Influence of Inlet Conveyance and Sea Level Rise on the Salinity Regime

Inlet Configuration

Historic evidence indicates that the Loxahatchee estuary was periodically closed and opened to the sea (McPherson, Sabanskas and Long, 1982). Due to active, long-shore sediment transport, the Jupiter Inlet was probably characterized by shifting sandbars through which ran a narrow and unstable channel. When James Henshall visited the area in the early 1880s, he observed the "Jupiter River flowing eastward, and over Jupiter Bar into the sea." He also described the difficulty of sailing through the inlet, which was "quite narrow" and had "an angle in its channel at the worst possible place" (Henshall, 1884). An aerial photo of the inlet from 1940s shows extensive flood shoals (sandbars that were formed by sands pushed into the inlet by tides), which would have limited the hydraulic conveyance of the inlet and the tidal range in the estuary. Under natural conditions with active sedimentation, the hydraulic conveyance of the inlet would be smaller than the conveyance under dredged conditions.

Sea Level Rise

Extensive analyses of tidal records indicates that global sea level has risen at a rate of approximately 2 mm per year for at least the last century or so (Douglas, 1991; 1992). Based on this estimate, the sea level around 1900 was about eight inches lower than the present level. A lower sea level means that a smaller range of tidal influence existed in the estuary.

Sea level rise was even more rapid prior to 1900. Approximately 15,000 years ago, the shore of the Atlantic Ocean was several miles east and more than 300 feet lower than its present location and altitude at Jupiter Inlet. From about 15,000 to 6,000 years ago, sea level rose at a rate of more than 3 feet per century. Tidal waters began to flood the estuary embayment. Prior to this time, the embayment was probably a flood plain or freshwater marsh (McPherson, Sabanskas and Long, 1982).

The rise of sea level has likely increased the range of tidal influence in the Loxahatchee River. If the sea level rise continues as predicted, it is foreseeable that the tide influence will move further upstream along with the sea level rise.

The Effects of Inlet Deepening and Sea Level Rise

The hydrodynamic/salinity model was applied as part of a preliminary investigation, to estimate the impacts of inlet dredging and sea level rise. This section outlines the preliminary results of six model simulations that have been completed. Freshwater input was kept constant through all six model simulations. Sea level and inlet depth were changed so that their effects on the position of saltwater wedge could be examined. Table 1 lists boundary conditions of the model simulations. Inlet depth was reduced from the current condition to average depths of 6, 4, and 2 feet subsequently. The current average depth of the inlet is approximately 8 - 10 feet. While the first four simulations were all at current sea level, simulation 5 was at the1900 sea level, which was 8 inches lower. Simulation 6 used the boundary condition of Simulation 1, except that sea level was one foot higher. The purpose of this simulation was to estimate the possible effects of future sea level rise.

Table 1. Boundary conditions of model simulations

Boundary Condition	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6
Sea level	Present MSL	Present MSL	Present MSL	Present MSL	1900 MSL	Present MSL + 1 ft
Discharge at Lainhart Dam	65 cfs	65 cfs	65 cfs	65 cfs	65 cfs	65 cfs
Total freshwater input to Northwest Fork	188 cfs	188 cfs	188 cfs	188 cfs	188 cfs	188 cfs
Freshwater input to North Fork	4 cfs	4 cfs	4 cfs	4 cfs	4 cfs	4 cfs
Freshwater input to South Fork	5 cfs	5 cfs	5 cfs	5 cfs	5 cfs	5 cfs
Inlet condition	1999 condition*	Average depth 6 feet	Average depth 4 feet	Average depth 2 feet	Average depth 2 feet	1999 condition*

To compare the range of tidal influence at various inlet depths, the location of 2 ppt salinity lines of model simulations 1 through 4 were plotted in Figure 10. The model output indicates that a shallower inlet would reduce the tidal influence on the river. For example, when the inlet depth is reduced to 4 feet by sedimentation, the 2 ppt line would move approximately 1 mile downstream from its present location under existing inlet condition. Therefore, dredging of the inlet in the past several decades has probably helped move the salt wedge upstream.

The two green lines in Figure 11 show the predicted locations of 2 ppt salinity lines at the estimated 1900 sea level (8 inches lower than current sea level) and a predicted future sea level (12 inches higher than current sea level). Comparing the results of Simulations 4 (current sea level with 2' inlet depth, Line D) and 5 (1900 sea level, Line E), the sea level rise itself in the past century would have moved the salt wedge upstream nearly 0.5 miles. The green line at the upstream end (Line F) is the predicted position of 2 ppt salinity line with an one foot sea level rise. If the inlet depth and freshwater inflow remain unchanged, the effect of sea level rise will therefore push saltwater further upstream from its present location (Line A).

DISCUSSION

Both field data analysis and the model output indicate a strong correlation between the amount of freshwater input and the estuarine salinity regime. The upstream portion of the Northwest Fork is especially sensitive to changes in freshwater input. Table 2 is based on the flow ~ salinity relationship presented in Figure 6. The table shows the flow rate of freshwater input that is required to maintain salinity below 2-ppt at various locations in the Northwest Fork.

Table 2. Freshwater inflow required to maintain high tide salinity below 2ppt at seven locations in the Northwest Fork

River Mile	Station #	Freshwater discharge into Northwest Fork above Kitching Creek (cfs)	Estimated discharge at Lainhart Dam(cfs)
6.5	#63	424	187
7.7	#64	202	89
8.6	#65	123	54
9.4	#66	64	28

The position of the salt wedge is the balance point between ocean tides and freshwater flow from the watershed. While a reduction in freshwater flow could cause saltwater intrusion, the modeling results illustrated that deepening of the inlet and rising sea level would also push the salt wedge further upstream. The preliminary modeling results indicate sea level rise and inlet dredging have significant impacts on the salinity regime in the Loxahatchee Estuary.

Based on the model simulations that had a shallower inlet and lower sea level, Table 3 lists the amount of freshwater that would be required under present conditions to maintain the 2 ppt line at locations that correspond to the 2ppt locations that occurred under the three historic scenarios.

The analysis outlined above indicates that sea level rise and inlet dredging have significant impacts on the salinity regime in the Loxahatchee Estuary. Due to the changes in sea level and inlet configuration, the amount of freshwater required to prevent salt water intrusion has increased if the management goal is to provide historic salinity condition in the river and estuary.

Table 3. Increased freshwater demand to prevent saltwater intrusion

Present and historic conditions	2 ppt line river mile	Required freshwater under historic condition (cfs)		Required freshwater under present condition (cfs)	
		Freshwater discharge at Lainhart Dam	Freshwater input to NWF	Freshwater discharge at Lainhart Dam	Freshwater input to NWF
A-Present condition	8.25			65	188
B-Inlet average depth 6 ft	7.7	65	188	85	246
C-Inlet average depth 4 ft	7.4	65	188	100	289
D-Inlet depth 4 ft, 1900 MSL	7.0	65	188	120	347

Inlet sedimentation is a very dynamic process. The modeling effort outlined in this document is just the first step of a preliminary investigation. More efforts are necessary to acquire historic bathymetry and sea level data and improve the accuracy of freshwater inflow data.

REFERENCES

Douglas, B. C., 1991. *Global sea level rise*, J. Geophys. Res., 96(C4), 6981-6992, 1991.

Douglas, B. C., 1992. *Global sea level acceleration*, J. Geophys. Res., 97(C8), 12,699-12,706, 1992.

Henshall, J. A., 1884. *Camping and Cruising in Florida*. Robert Clarke & Co., Cincinnati, 1884.

McPherson, B.F., Sabanskas, M., & Long, W., 1982. Physical, Hydrological, and Biological Characteristics of the Loxahatchee River Estuary, Florida. USGS Water-Resources Investigations, Open file report, 82-350.

Russell, G.M., McPherson, B.F., 1983. Freshwater Runoff and Salinity Distribution in the Loxahatchee River Estuary, Southeastern Florida. USGS Water-Resources Investigations Report, 83-4244.

Russell, G.M., Goodwin, C.R., 1987. Simulation of Tidal Flow and Circulation Patterns in the Loxahatchee River Estuary, Southeastern Florida. USGS, Water-Resources Investigations Report 87-4201. Tallahassee, Florida, 1987.

USACE, 1996. Users' Guide to RMA2 Version 4.3. US Army Corps of Engineers, Waterways Experiment Station, Hydraulic Laboratory.

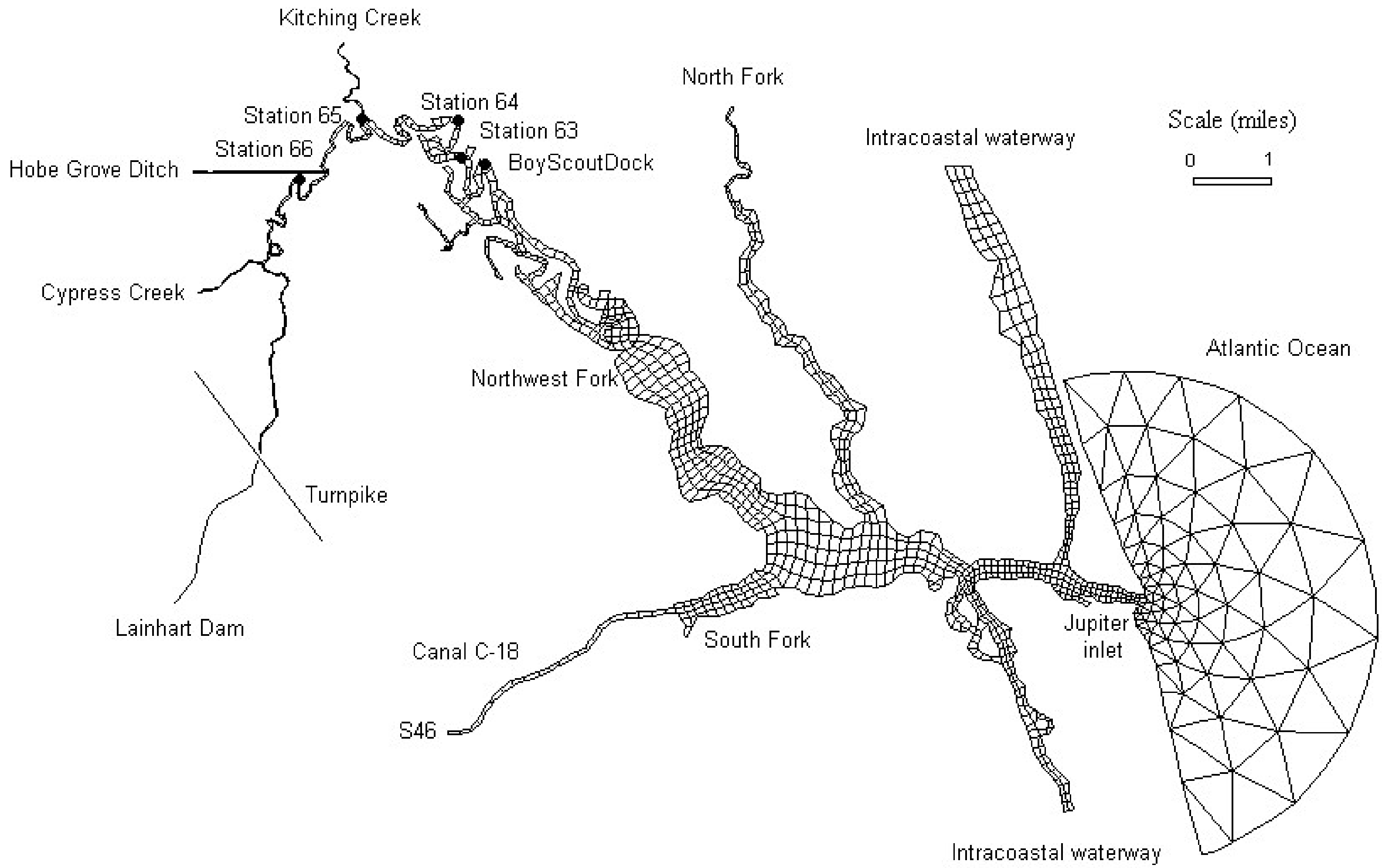

Figure 1. Finite element mesh of Loxahatchee Estuary Salinity Model

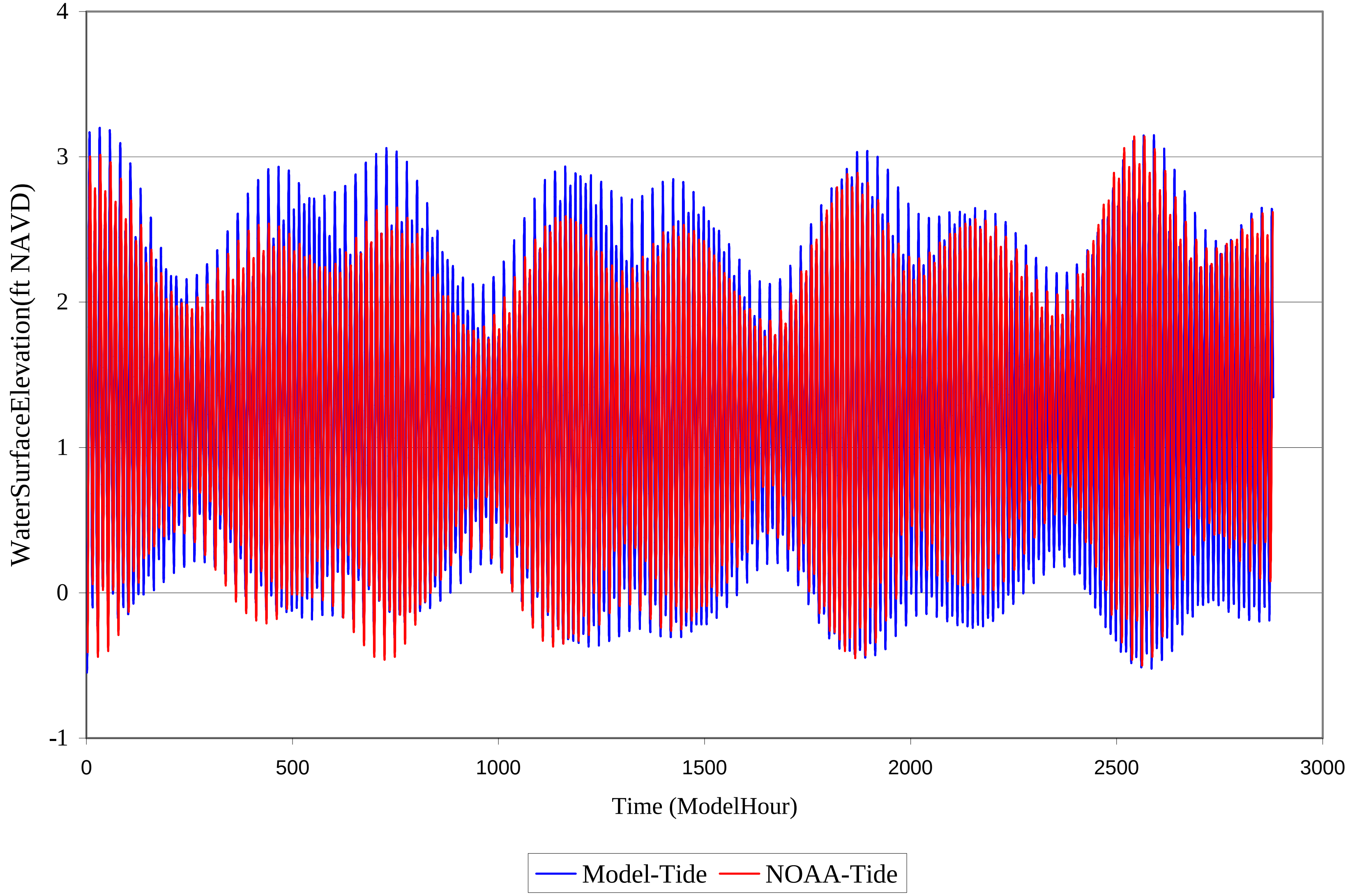

Figure 2. Model output vs. NOS data: Tides at BoyScoutDock, January 1 - April 30, 1999

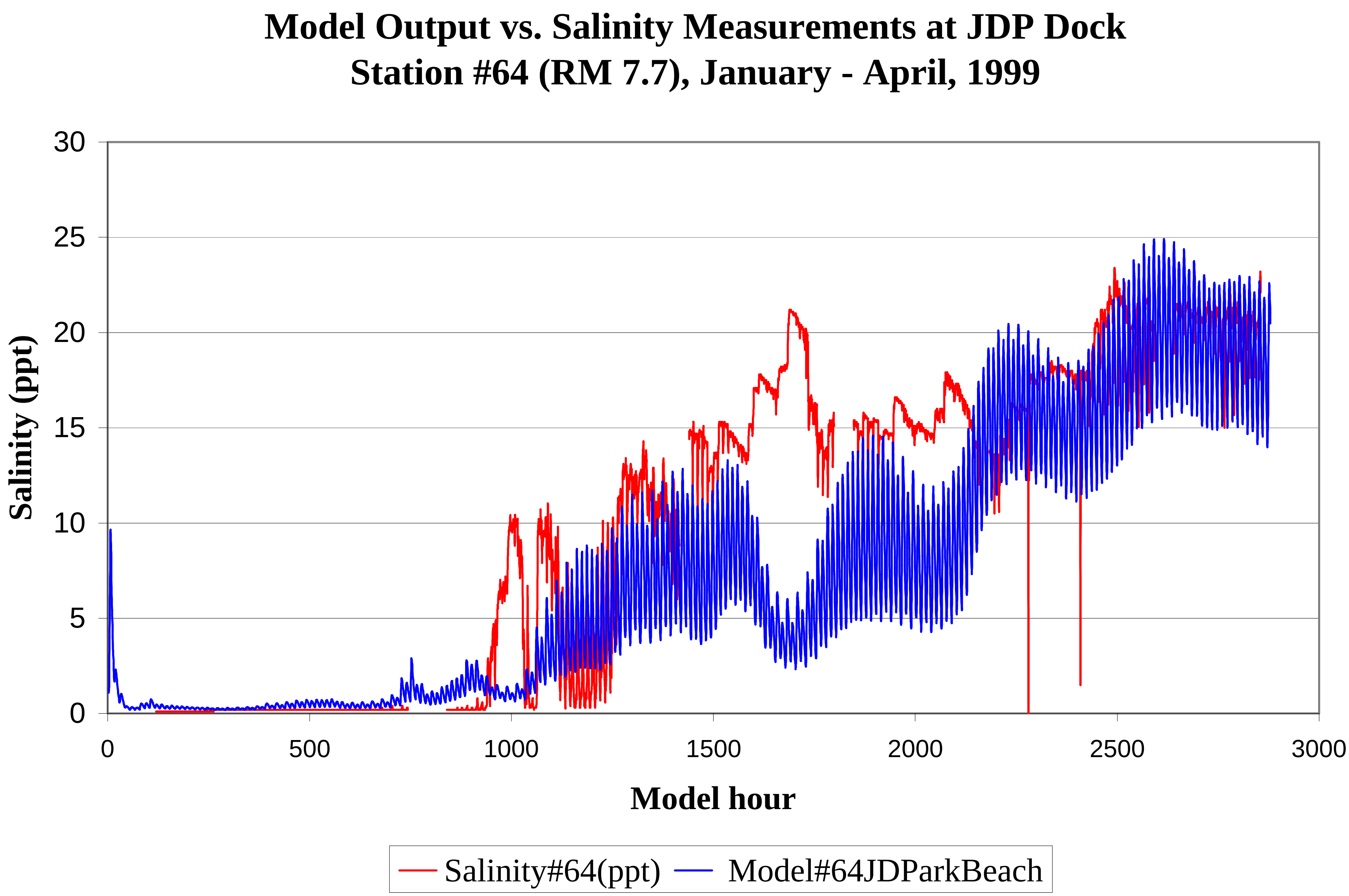

Figure 3. Comparison of model output and field record at Station 64 (RM 7.7)

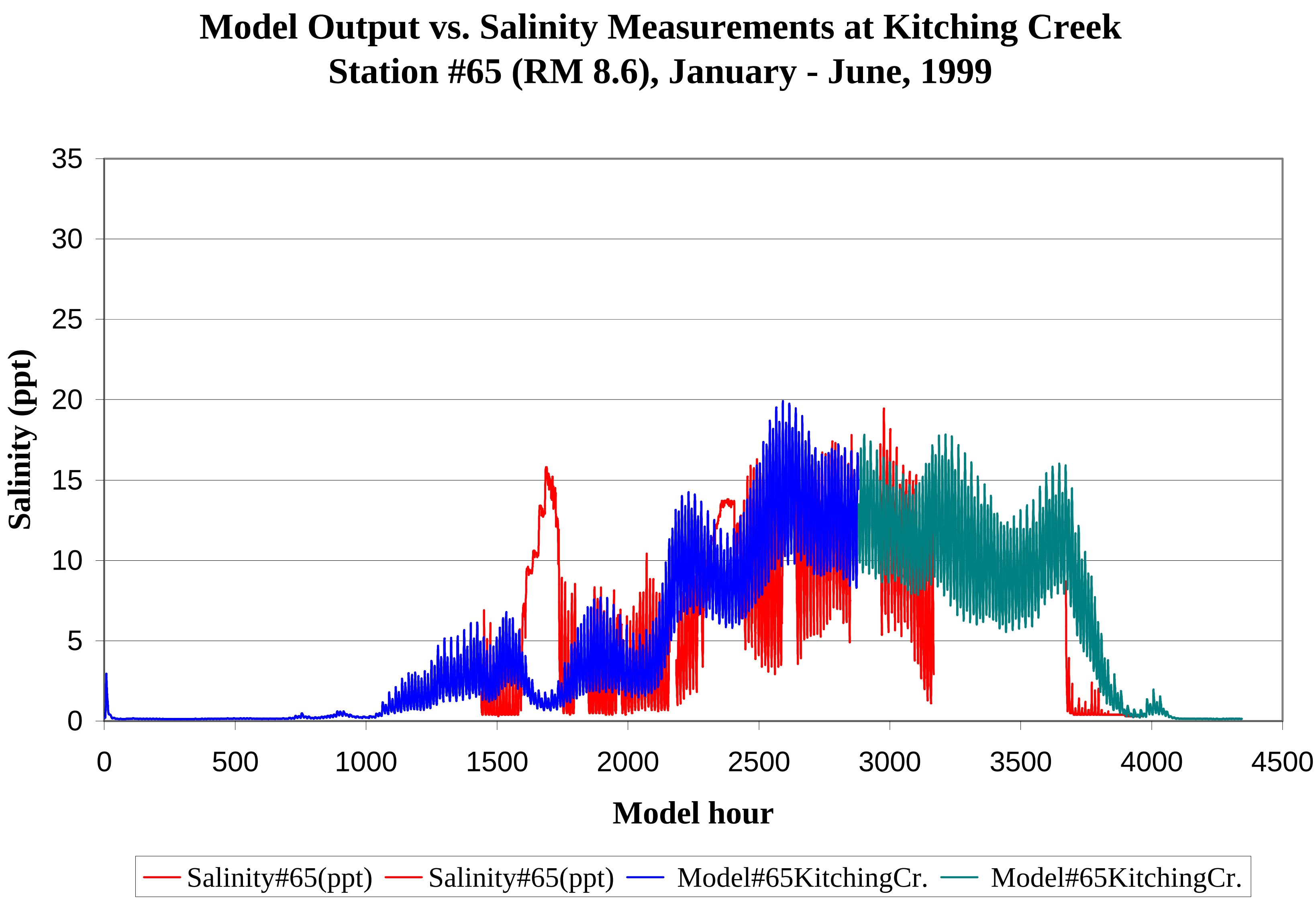

Figure 4. Comparison of model output and field record at Station 65 (RM 8.6)

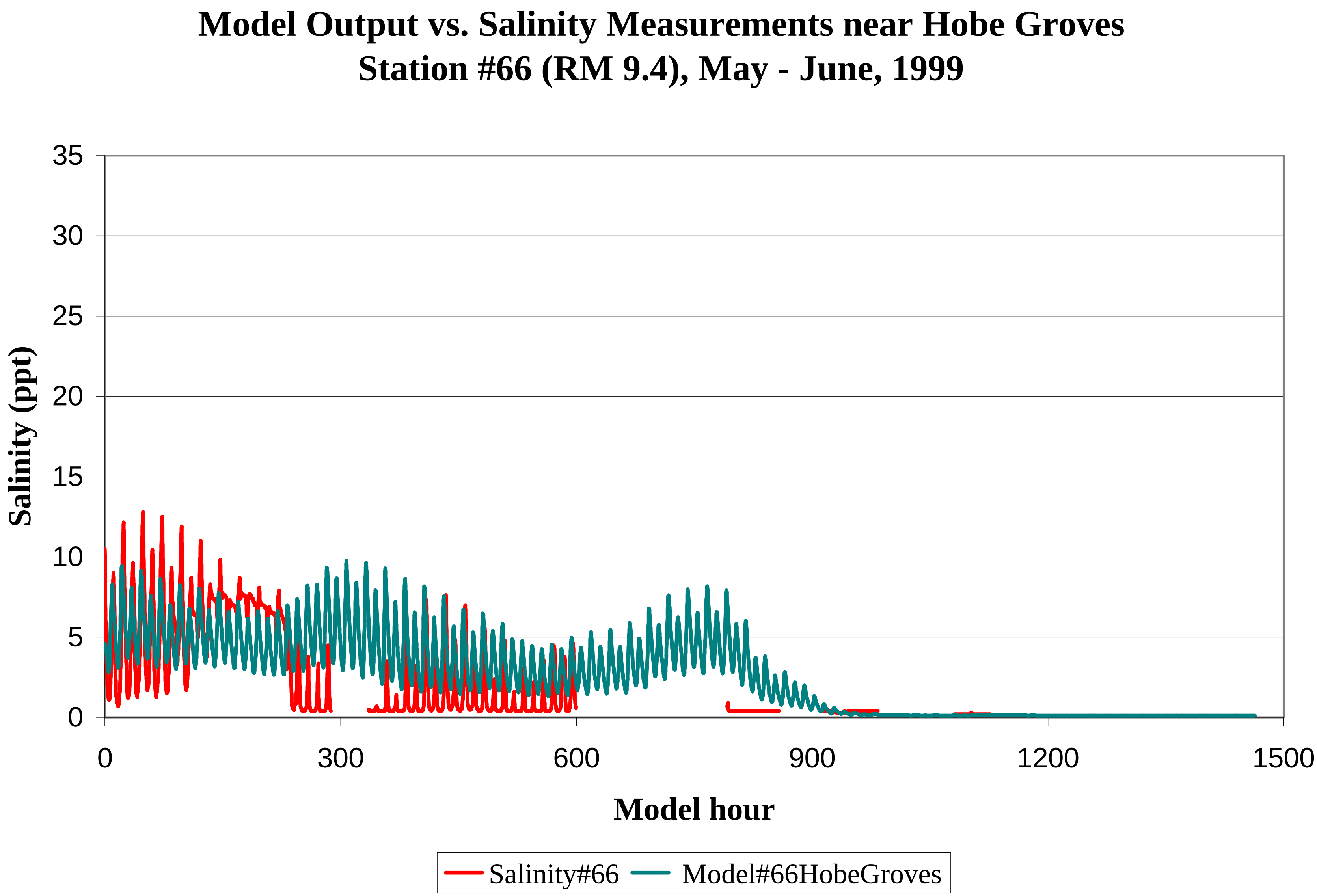

Figure 5. Comparison of model output and field record at Station 66 (RM 9.4)

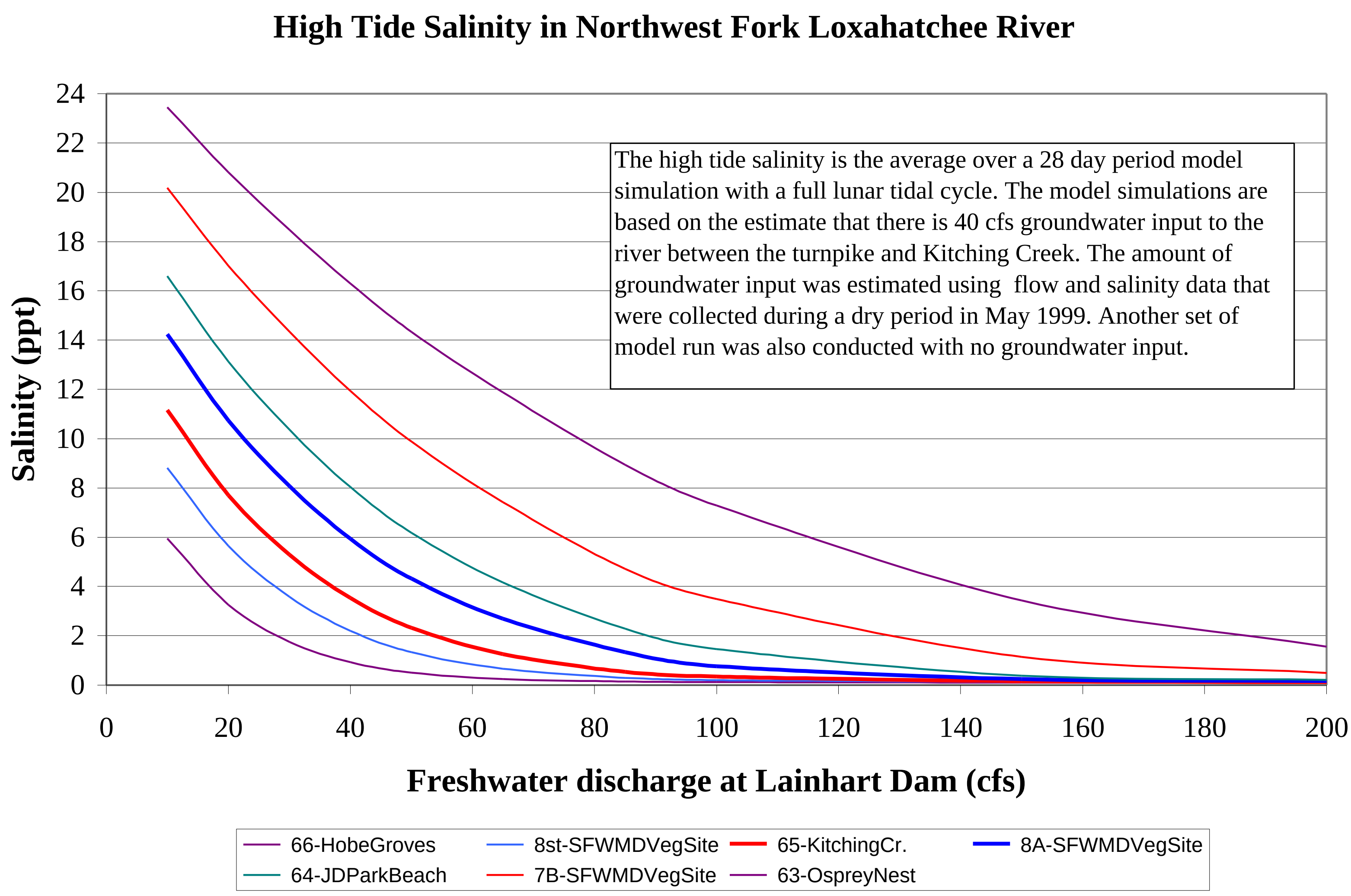

Figure 6. The relationship between high tide salinity and the amount of freshwater inflow

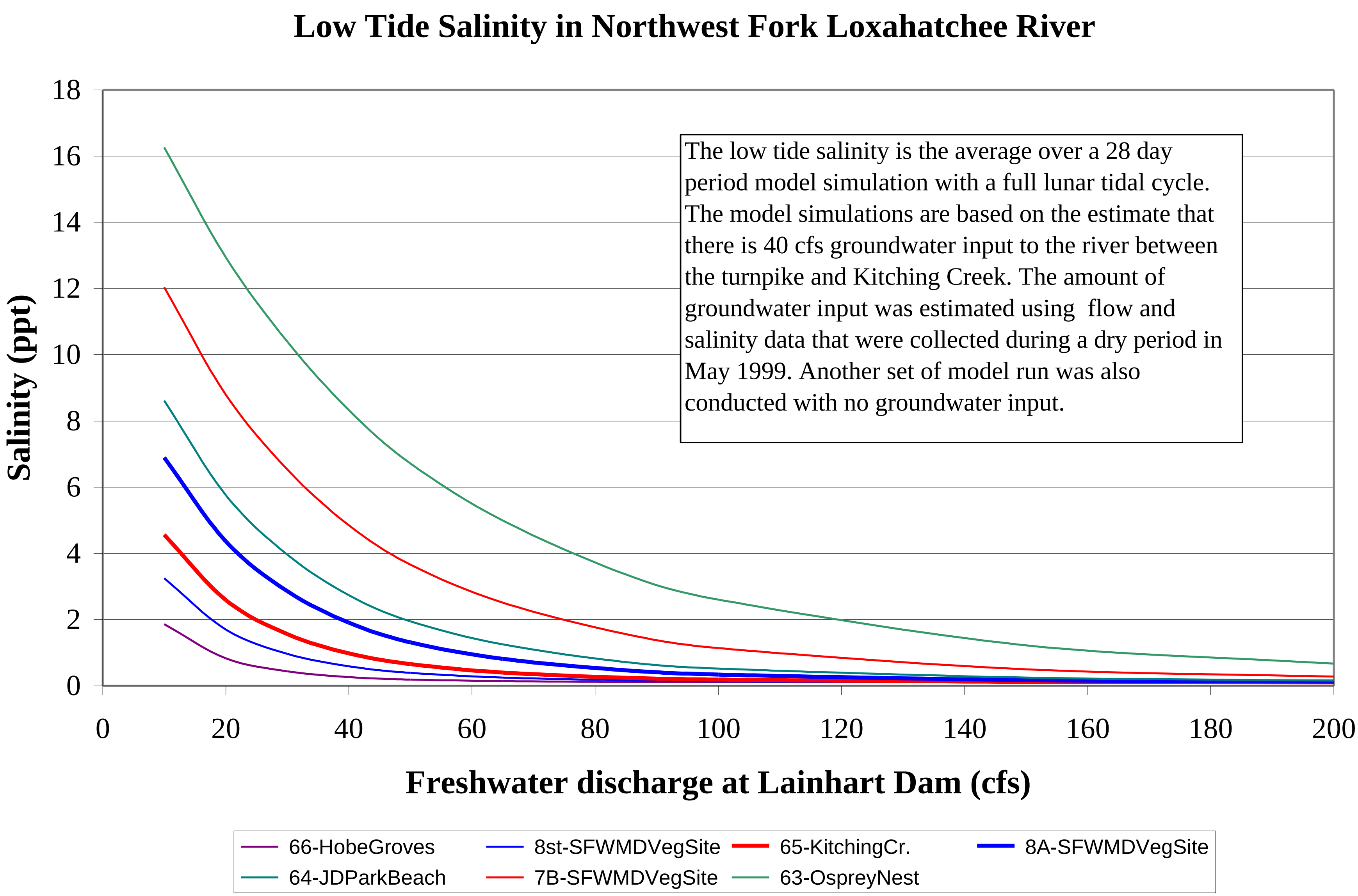

Figure 7. The relationship between low tide salinity and the amount of freshwater inflow

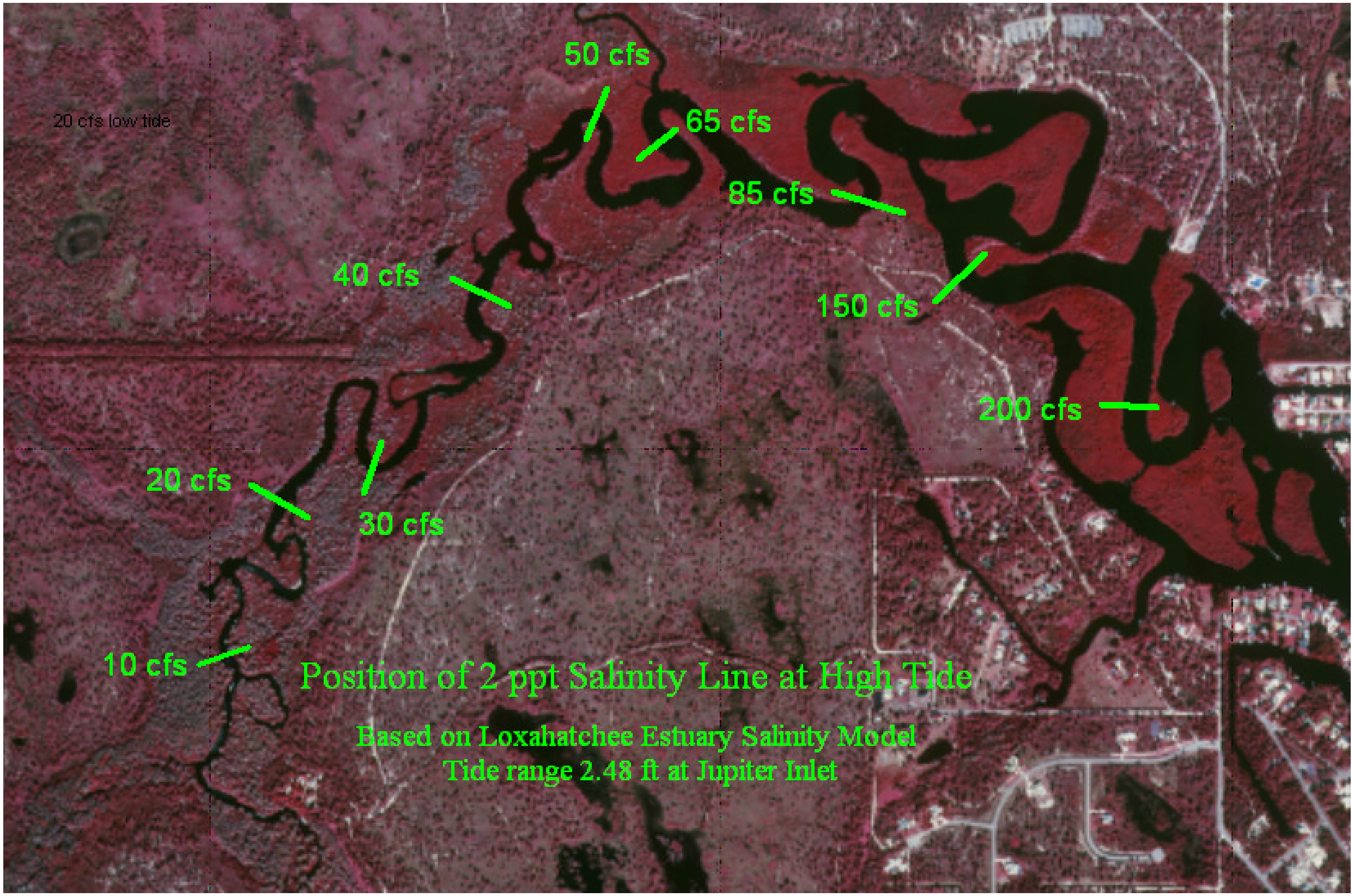

Figure 8. 2-ppt salinity line position at high tide
2-ppt lines are labeled with discharge at Lainhart Dam

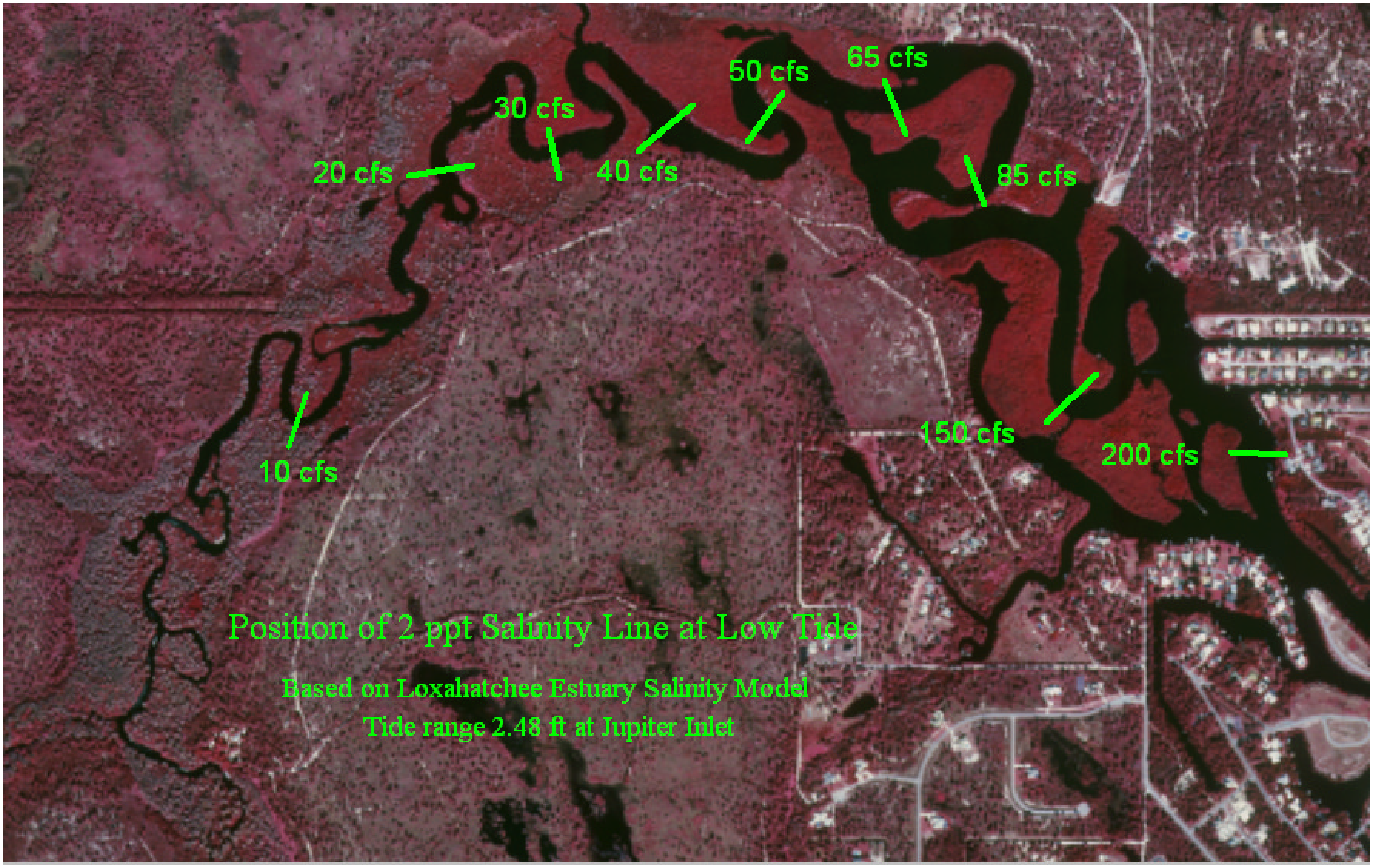

Figure 9. 2-ppt salinity line position at low tide.
2-ppt lines are labeled with discharge at Lainhart Dam

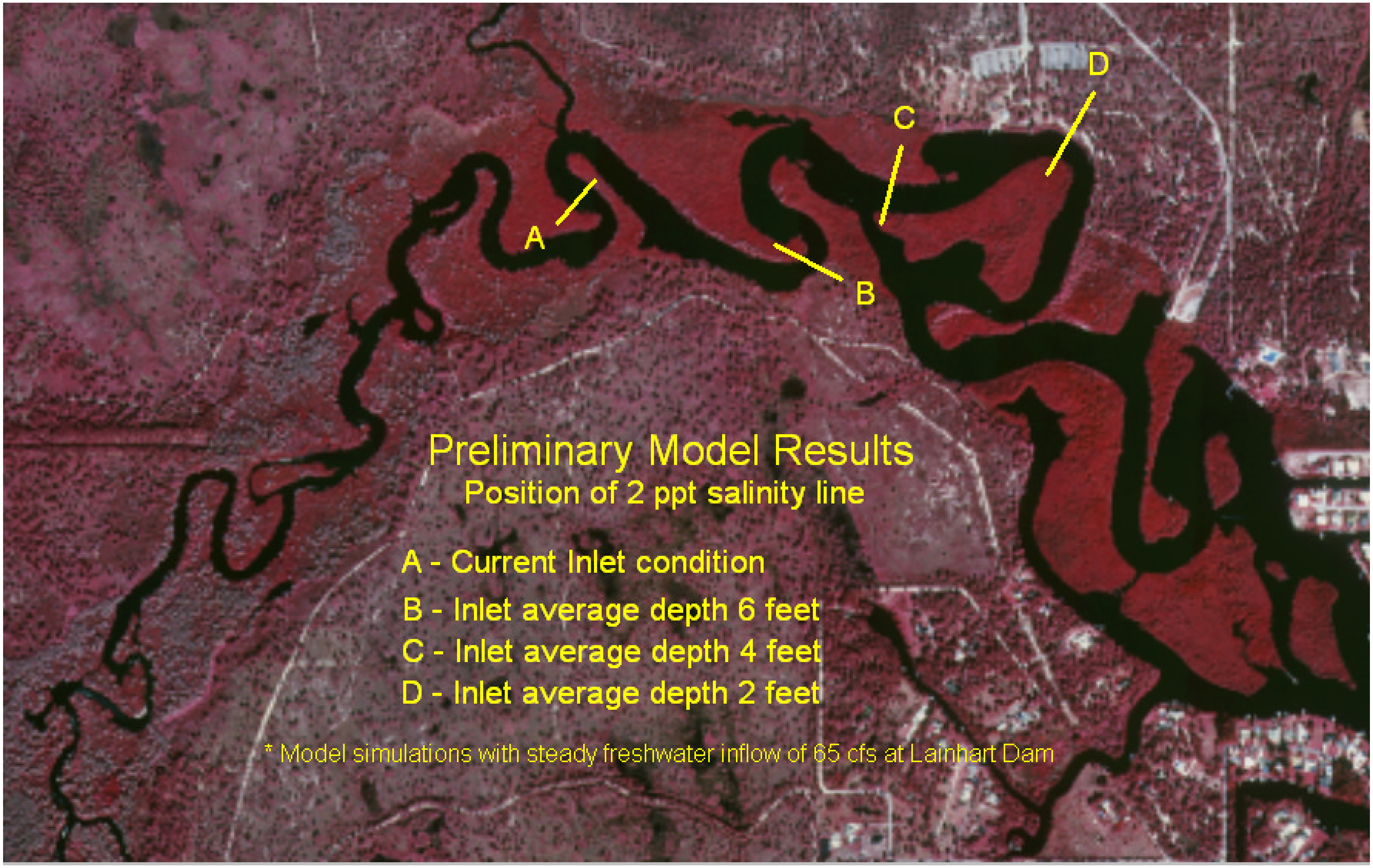

Figure 10. 2-ppt salinity line position at various inlet depths.
2-ppt lines are labeled with depth at Jupiter Inlet

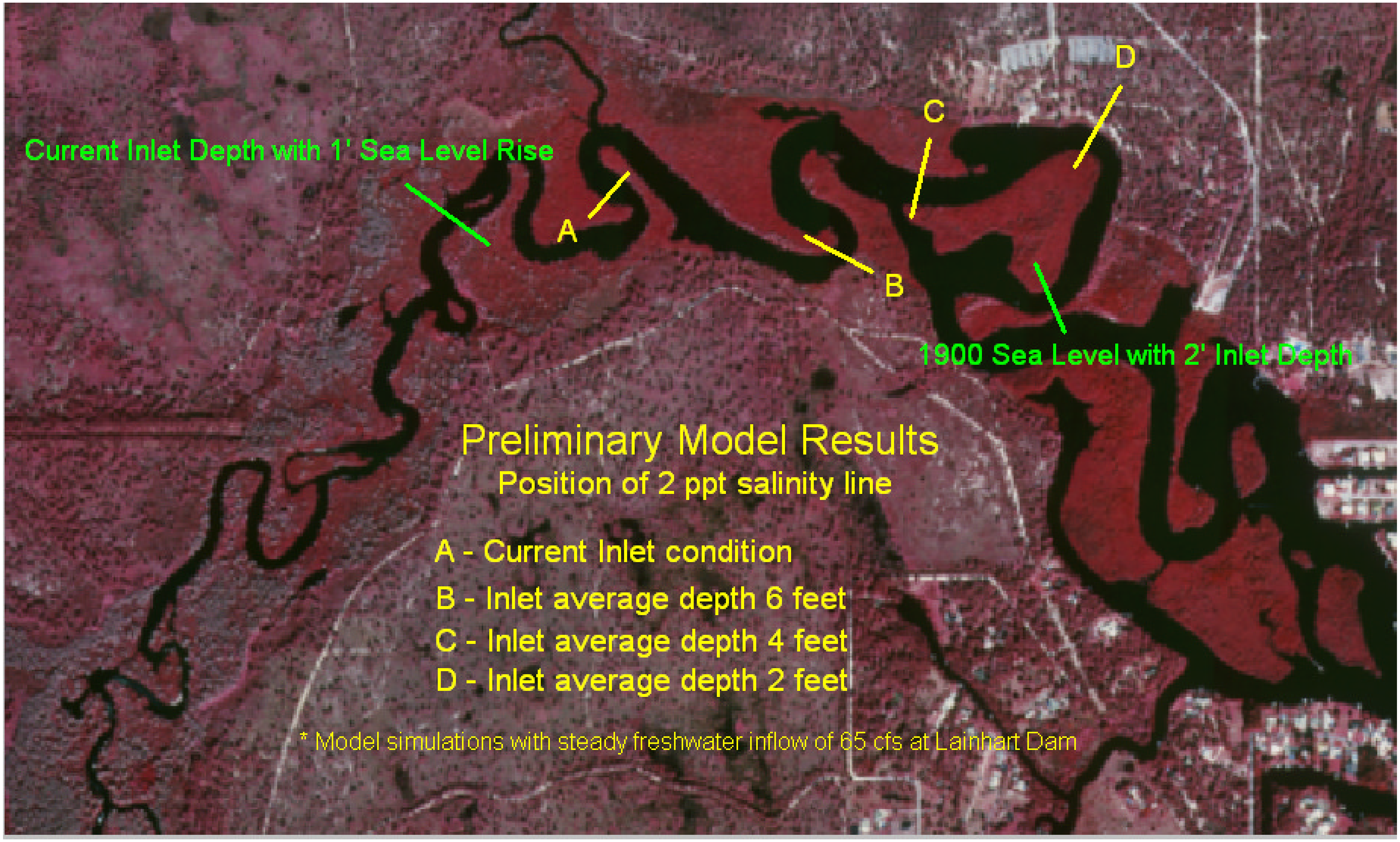

Figure 11. 2-ppt salinity line position at various inlet depths and sea level.
2-ppt lines are labeled with depth at Jupiter Inlet and sea level